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Fibre Bragg Gratings, Towards a Better Thermal Stability at High Temperatures

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Abstract

Regenerated fibre Bragg gratings (RFBG) are obtained by heating an original seed grating until its reflection practically vanishes, which is followed by the growth of a new reflection band. Advantages of RFBG for sensing purposes are the longer lifetime and higher thermal stability at higher temperatures, as they have been observed to survive temperatures in the range 1300-1500 °C. The thermal stability of the RFBG permits several applications not attained by standard Bragg gratings.

Keywords: Fibre Bragg grating; regenerated grating; sensors; fibre optic sensor

1. Introduction

Fibre Bragg gratings (FBG), a periodic longitudinal modulation of the refractive index along the fibre core were discovered in 1978 [Hill et al.]. The main feature of the FBG is the rejection band centred at the Bragg wavelength (λ_B=2n_{eff} Λ, where Λ is the spatial pitch of the refractive index modulation and n_{eff} is the effective index of the propagated mode) when the grating is illuminated by a broadband source.

The use of interferometer methods [Meltz et al. (1989), Wang et al. (2001), Hill et al. (1993)] to write FBG allowed their use in a broad spectral range, from the visible to near-infrared, profiting from the NIR single-mode fibre optic as well miniaturized optical sources and detectors developed for fibre optic communications.

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Interferometer methods use transversal illumination of the fibre, which benefits mass production of gratings and assure repeatability of their spectral characteristics.

One important aspect in FBG applications is the dependence of the Bragg wavelength with external parameters, like strain, ε, or temperature, T. In fact, the change in the Bragg wavelength with these two physical parameters was reported about the same time of their discovery [Hill et al. (1978)], and is governed by:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha + \xi)\Delta T \tag{1}$$

Nomenclature

λ_B	Bragg wavelength
Λ	spatial pitch of the refractive index modulation along the fibre
ε	strain
p_e	effective photo-elastic constant for Silica
α	thermal expansion coefficient
ξ	thermo-optic coefficient
T	temperature

where α is the thermal expansion coefficient, ξ is the thermo-optic coefficient and p_e resumes the photo-elastic effect contribution of the fibre optic; for standard silica fibres these values are, respectively, $0.56 \times 10^{-6}\ K^{-1}$, $8.0 \times 10^{-6}\ K^{-1}$ and 0.22. The dependence described by eq. (1) allows the FBG to be used a transducer for sensing strain or temperature directly.

A helpful characteristic for using the FBG in sensors is their spectral encoding, which eliminates the need of reference channels or periodic calibration when the spectrum of the grating is measured. Other fibre inherent characteristics, like the small footprint, chemical inertness to a large variety of products, electromagnetic immunity, reduced volume and mass, are also very attractive to sensing applications, particularly in hostile environments. Furthermore, the spectral encoding of the FBG allows a large number of gratings, with different Bragg wavelengths, to be interrogated in an optical division multiplexing scheme along a single optical link; this allows further reduction in the volume and weight of associated cabling. In fact, FBG sensing is a current practice in several engineering areas as, e.g., monitoring of large structures or historical buildings [Lima et al. (2008)], biomedical engineering [Wehrle et al. (2001)] or power generators start-up control [Martelli et al. (2012)].

Even if FBG are extensively used for monitoring purposes, several sensing applications still lie outside their practical application, most of them related to industrial processes in high temperature like, e.g., oil cracking and refining, fluid metal processing, high temperature chemical reactors. This happens to occur due to the bleaching of the FBG when subjected to higher temperatures. Recently, a new classification of FBG types was proposed [Canning (2008)], which incorporates and clarifies their stability at different temperatures.

The pursuit for better stability at high temperatures was carried out by several techniques. Speciality fibres were drawn using different dopants in the glass composition [Butkov et al. (2006), Groothoff and Canning, (2004)] or other materials [Grobnic et al. (2007)], quenching and annealing processes were applied either as pre- or post grating inscription[Chisholm et al. (1998), Aslund and Canning (2000), Coradin et al. (2013)], femtosecond laser pulses were used to write the grating by a point by point method [Martinez et al. (2004)], among others. Resulting performance increased from a few hours at 800°C [Groothoff and Canning (2004)] – using a Boron co-doped fibre optic – to about 300 hours at 600°C in standard G.652 telecommunications grade fibre optic [Oliveira et al. (2011)], as depicted in the graph on Fig. 1. Instead of saturating the FBG during the writing procedure, that last grating was recorded in a regime leading to a still moderately weak grating at the end of the inscription process. The grating reflectivity decays initially when a high temperature ramp is applied, stabilizes after a few hours and then presents stable long term behaviour. The observed small slope in the reflected signal allows extrapolating a few thousand hours with good signal to noise ratio, which is adequate for several sensing applications. In the same graph it is also shown the behaviour for a regenerated FBG written in the same type of fibre and pre-heated to about 850°C.

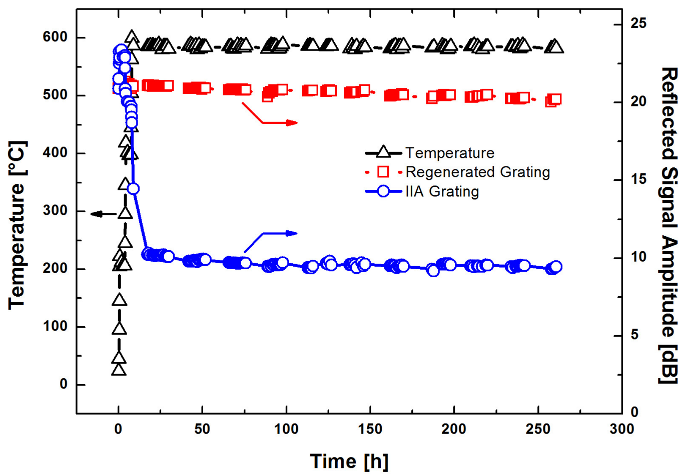


Fig. 1. (circle) 300h thermal stability of the amplitude of the reflected signal of enhanced Type IIA FBG written in G.652 fibre; for comparison the stability of a regenerated FBG in G.652 fibre is also shown (square). The temperature evolution is shown by the triangle marks. The lines are only guides for the eye.

In the proposed new classification scheme of FBG [Canning (2008)] a new type was introduced that presents pronounced stability at higher temperatures, the so called regenerated fibre Bragg gratings (RFBG), now considered as a proper FBG class. The regeneration of the FBG spectrum was initially observed as the so called Chemical Composition Gratings [Fokine (2002)], but the actual name is prevalent in the literature. The main feature of RFBG is the thermal bleaching – at constant temperature – of their optical spectral band, followed by the growth of a new one, that stabilizes afterwards. Typically the regeneration process starts with the recording of a strong, saturated, seed FBG grating, which is heated to a temperature in the order of 800-900 °C. If the grating is maintained at that temperature, the spectrum vanishes in a few minutes, followed by the growth of the regenerated spectrum, as illustrated in the graph in Fig.2. The regenerated spectrum presents characteristics of a weak FBG, with narrower bandwidth and smaller amplitude, as it can be seen in Fig. 3. If a close monitoring of the reflection spectrum is done during the regeneration process, it can be observed that the process initially presents the decrease in the reflected intensity and spectral bandwidth, followed by the appearance of a dip in the central spectral region. The dip increases until the spectrum vanishes and a new reflection starts to grow at the same optical wavelength [Marques et al. (2012)]. The RFBG shows increased temperature stability, surviving heating to ~ 1500 °C [Aslund et al. (2010)] ; amplitude and wavelength stability have been already studied over a time span of 9000 hours [Laffont et al. (2013)], indicating that such grating family can have widespread applications.

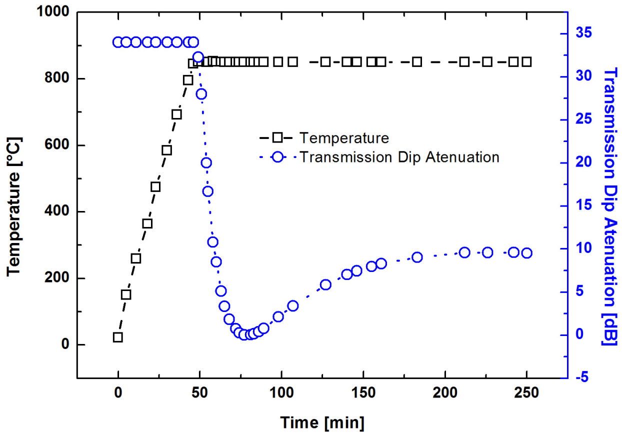


Fig. 2. Thermal regeneration cycle for a fibre Bragg grating, the squares depict the temperature evolution as function of the time; circles show the amplitude of the spectral transmission dip.

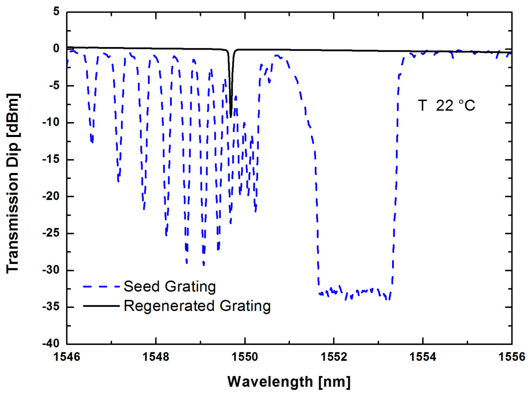


Fig. 3. Transmission spectra of a fibre Bragg grating: (dashed line) – original saturated seed grating at room temperature and (continuous line) – regenerated grating, after cool down to room temperature.

2. Thermal monitoring of Diamond deposition process

Diamond is presently applied in a board range of different applications, as result of its characteristics, including high hardness, wear and corrosive resistance, high thermal conductivity, excellent response in terms of biocompatibility and non-toxicity and adhesion of the diamond to biological material [Gracio et al.) (2010), Alberto et al. (2012)]. The number of available techniques to obtained diamond films is vast. Nevertheless, regardless of the deposition technique, the temperature is a critical parameter that plays a fundamental role in this process. The morphology of the deposited crystals, including the growth rate, crystal size and also its orientation is dependent of the temperature.

Traditional methods used to control the temperature present experimental limitations since sometimes the sensor is not placed on the target of interest, leading to inaccuracies in the temperature estimation. In this application, RFBGs were used in the real time thermal monitoring of the diamond deposition process.

Seed FBGs were inscribed onto hydrogen loaded standard G.652 fibre, using a KrF excimer pulsed laser. The residual hydrogen was removed before the regeneration process that occurred at 900 ºC. This heating was suspended only 8 h after the regeneration process in order to stabilize the thermal properties of the RFBGs.

The diamond deposition was realized in a hot filament chemical vapour deposition (HFCVD) system, described in [Santos (2007)], equipped with a vacuum pressure feed-through for optical fibres, from OZ Optics, allowing the passage of the optical signal from the outside to the reactor interior, and consequently the real time monitoring of the deposition process Fig.4 (left). The gas mixture used in the deposition was constituted by Ar (162.4 sccm), CH_4 (1.6 sccm) and H_2 (36.0 sccm). The reactor pressure, distance between the fibre and the upper and lower tantalum filaments, Fig. 4 (centre), were 30 Torr, 9 mm and 4 mm, respectively. The RFBGs were carefully positioned close to the two filaments. As interrogation system was used a sm125-500 from Micron Optics.

Figure 4 (right) shows the temperature evolution during the 3 h of the diamond deposition. In the first 33 minutes, the temperature increase from ambient temperature to 742 ºC, corresponding this period to the starting up of the reactor. After the reactor' conditions were stabilized (filament's current and voltage), the diamond deposition began and no significant variations in this parameter were detected. In this period (3 h) an average temperature value of 720 ºC is noticed (solid line in Fig. 4 (right)). The end of the deposition and the shutdown of the system were identified by an accentuated decrease of the temperature.

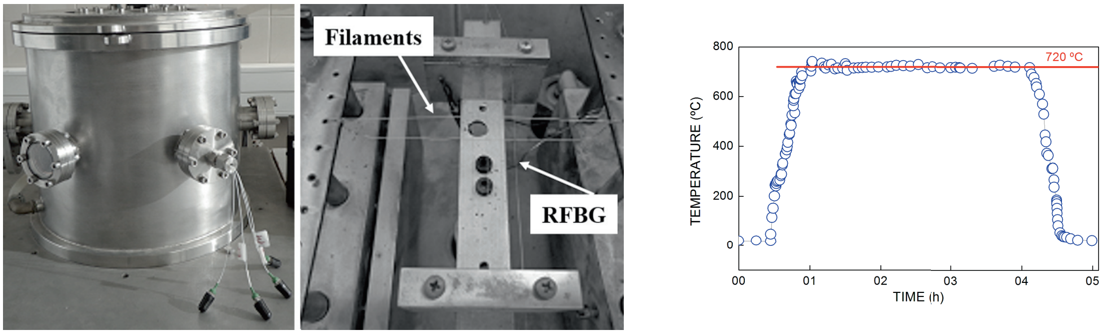


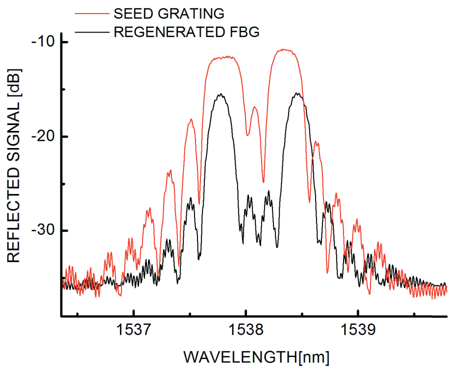
Fig. 4. (left) External view of the CVD reactor with fibre optic feed-through and (centre) internal view of the heating filaments and fibre with RFBG. (Right) Temperature evolution during the diamond deposition process, square are experimental RFBG measurements, the solid line depicts the average temperature at the deposition plateau.

In conclusion, RFBGs reveal a suitable solution for the on-line monitoring of the diamond deposition. According with the results obtained, this process occurs around 720 ºC, considering the experimental conditions above mentioned. The control of the temperature can contribute to a better understanding of the process, leading to a higher control of the deposition, and consequently the ability to obtain tailored diamond coatings. Additionally, the Bragg gratings sensors allow a multi-distributed monitoring, being an important feature when coating complex geometries, such as 3D molding tools are considered.

3. Temperature dependence of fibre birefringence

Stress induced high birefringence fibre optics present stress applying regions in the glass structure that splits the FBG spectra in two components, accordingly to the main values of the refractive index for two orthogonal directions. One advantage of high birefringence (HiBi) FBG is that the birefringence sensitivity to the temperature has an opposite sign to the sensitivity to strain; in this situation a measurement using both polarization bands can overcome the crosstalk pertinent to standard FBG. In fact, HiBi gratings were used to monitor two or three measurands simultaneously.

Fig.5 (left) shows the reflection spectra from a HiBi FBG written in internal elliptical cladding (IEC) fibre. It can be seen, from the central wavelength of the spectrum, that the birefringence returns approximately to the same value after the regeneration process, which occurred at 820°C, This implies that the stress distribution on the fibre internal structure is preserved after the heating at such high temperatures, a result that was not present on the first studies on this subject [Ramaswamy et al. (1979)], where the authors reported a considerable residual change in the birefringence value after the initial heating.



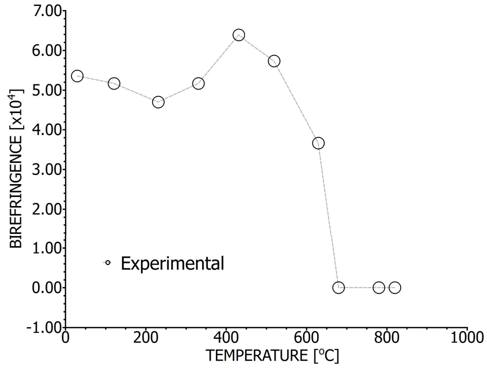


Fig. 5. (left) Optical reflection spectra of a FBG before (seed) and after the regeneration process; (right) evolution of the birefringence with temperature (lines are only a guide for the eye).

In the same figure (right) the evolution of the birefringence with temperature during the regeneration process is presented, where a noticeable non linear behaviour is observed. This behaviour has been previously observed by measuring the polarization beat length from photographs of the lateral scattering along the fibre propagation axis [Ramaswamy et al. (1979)] but the initial results where not able to show the complete behaviour depicted in Fig. 5. Further work extended the study by measuring the transmitted intensity on longer fibre lengths [Rashleigh and Marrone (1983)]. However, the reversibility of the birefringence was only a guess because of devitrification of the samples. One advantage of using HiBi FBGs is that the sensing region (the length of the FBG) is in the order of the beat-length (~ mm) whereas in the past the polarization studies by lateral scattering or interference measurements used fibre lengths with tens of the beat-length. So, the HiBi FBG measurement is more spatially localized and can sense the local change to the birefringence. In fact, several high birefringence fibre optics were studied with FBG using their spectral properties [Abe et al. (2013)].

4. Design and fabrication of accurate optical filters

A very interesting application of RFBG in the production of fibre optic in-line devices was recently published [Marques et al. (2012)]. The idea came from the observation of the central dip in the reflection spectra as the regeneration process occurs. By removing the fibre from the heating element and quenching it to ambient temperature it is possible to freeze the spectral shape in a reproducible and stable form. This allows to obtain reflective notch filters with a given frequency and bandwidth (using different gratings lengths). The dip amplitude and the bandwidth don't change if the filter is used at different temperatures (only the central frequency changes).

5. Conclusion

Regenerated fibre Bragg gratings can be applied to several sensing applications that were outside the range of standard gratings. The production process is not cumbersome, but still one drawback is the glass condition after the high temperature initial heating, which turns brittle. Solutions were presented in the packaging of the grating with silica, ceramic, carbon fibre or steel tubing before the regeneration, which helps to have a more robust sensor. Other solutions are still to be investigated concerning the heating with different heat sources (lasers, e.g.), working in vacuum or inert gas filled environments and fibre surface post-processing (flame brush techniques, e.g.) in order to enhance the characteristics of the fibre external surface. Another possibility is the coating of the fibre with proper metals before the regeneration. Proper high temperature resistant materials are also needed for the secondary coating and cabling of the sensing region.

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